


CFD Vision 2030 CFD Study

A Pathway to Revolutionary Computational Aeroscienes


Mujeeb R. Malik

Senior Scientist for Aerodynamics

NASA Langley Research Center

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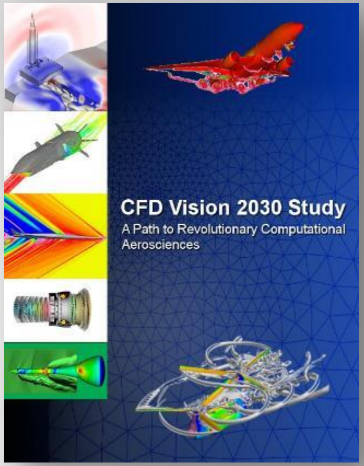
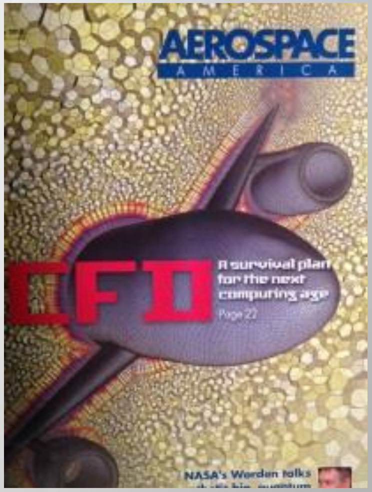
CFD Vision 2030 Study

- NASA commissioned a one-year study (completed March 2014) to develop a comprehensive and enduring vision of future CFD technology and capabilities:
  - **"…provide a knowledge-based forecast of the future computational capabilities required for turbulent, transitional, and reacting flow simulations…"**
  - **"…and to lay the foundation for the development of a future framework/environment where physics-based, accurate predictions of complex turbulent flows, including flow separation, can be accomplished routinely and efficiently in cooperation with other physics-based simulations to enable multi-physics analysis and design."**

NASA CR 2014-218178





Background: CFD Impacts 3 NASA Mission Directorates

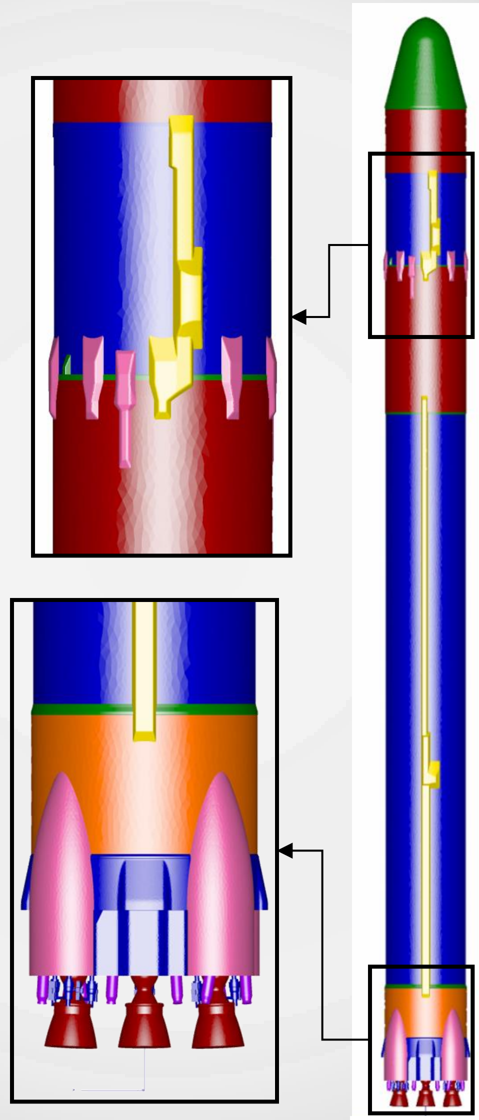
CFD is a cross-cutting technology

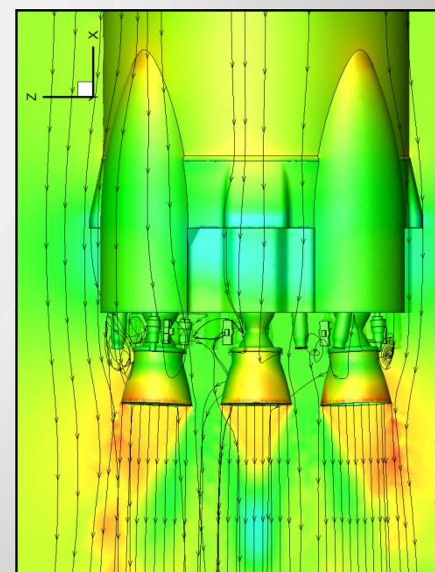
- **Aeronautics Research Mission Directorate (ARMD):**
  - It supports three of the ARMD strategic thrusts, and the associated “outcomes”
  - Plays an important role in subsonic and supersonic civil aircraft and rotorcraft technology development
  - Basic computational tool development
    - OVERFLOW, CFL3D, ARC3D, Wind-US, Vulcan …
    - FUN3D, USM3D, CART3D…
- **Human Exploration and Operations (HEOMD):**
  - Development of Space Launch System, Orion
- **Science (SMD):**
  - Planetary entry systems (MSL/Curiosity)
  - Climate, weather, environment

Background - 1: CFD Impacts Commercial Space Industry

- Using NASA's FUN3D as primary CFD tool for:
  - Falcon 1 ascent aero
  - Falcon 9 ascent aero
  - Lower speed Dragon reentry aero
- Full, detailed vehicle models, including up to 18 plumes
- Performing hundreds of simulations per vehicle across the flight envelope
- CFD predictions agree very well with all flight and wind tunnel data

Images and Information Courtesy of SpaceX





Background -2: CFD Impacts Aeronautical Industry

Substantial CFD Utilization **Some CFD Utilization** **Limited CFD Utilization**

Key Enablers Include High Performance Computing and Physics-based Design/Analysis/Optimization

Courtesy of Boeing

Background-3: Impact on Aircraft Efficiency and Wind Tunnel Testing

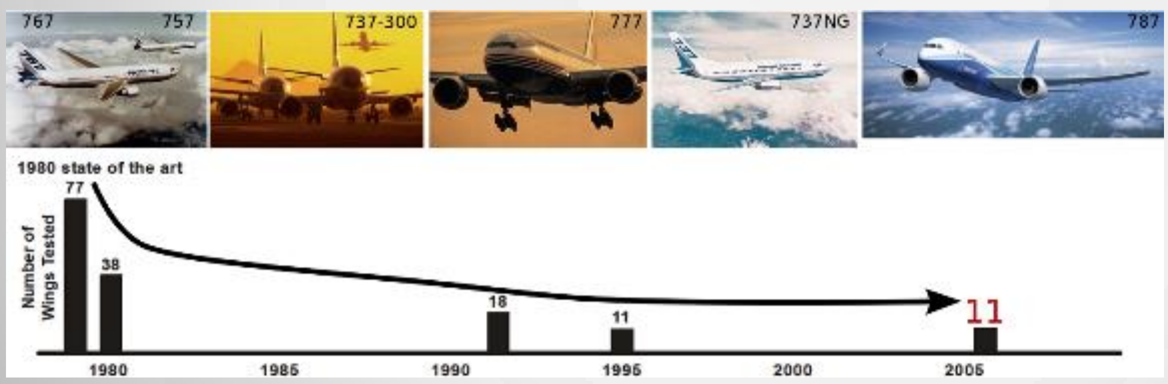
"Since the first generation of jet airliners, there has been about a 40% improvement in aerodynamic efficiency and a 40% improvement in engine efficiency … about half of that has come from CFD."

(Robb Gregg, BCA Chief Aerodynamicist)

- Significant decrease in wind-tunnel testing time since 1980's reduces cost and enables faster market readiness
- Reduction in testing time largely enabled by availability of mature and 'calibrated' advanced CFD
- The next major cost reduction requires breakthrough in the development of advanced turbulence models

Background – 4: CFD Challenge

- **CFD has drastically reduced testing for cruise design**
  - Attached flow, well predicted by current turbulence models
- **Testing still required for off-design (e.g., high-lift) conditions, even for conventional configurations**
  - Flow separation is the key issue
- **Increased testing will be required for innovative configurations**
  - Prediction of flow separation and transition are key physics issues



Inability to further reduce number of tests due to deficiency in modeling of turbulent flow physics

Vision 2030 Study Charter

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Vision 2030 CFD Team Members

NASA Technical Monitor – **Mujeeb Malik**

Jeffrey Slotnick
Principal Investigator
Boeing Research & Technology
jeffrey.p.slotnick@boeing.com

Abdi Khodadoust
Project Manager
Boeing Research & Technology
abdollah.khodadoust@boeing.com

Juan Alonso
Stanford University

David Darmofal
Massachusetts Inst. Of Technology

William Gropp
National Center for Supercomputing Applications

Elizabeth Lurie
Pratt & Whitney – United Technologies

Dimitri Mavriplis
University of Wyoming

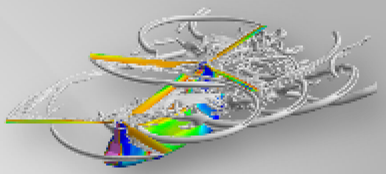
Extended Vision 2030 Team:

- Joerg Gablonsky, Mori Mani, Robert Narducci, Philippe Spalart, and Venkat Venkatakrishnan – *The Boeing Company*
- Robert Bush – *Pratt & Whitney*

Vision 2030 Overview

- Elements of the study effort:
  - **Define and develop CFD requirements**
  - **Identify the most critical gaps and impediments**
  - **Create the vision**
  - **Develop and execute a community survey and technical workshop to gain consensus and refine the vision**
  - **Develop a detailed technology development roadmap to**
    - **capture anticipated technology trends and future technological challenges,**
    - **guide investments for long-term research activities,**
    - **and provide focus to the broader CFD community for future research activities**

Vision of CFD in 2030

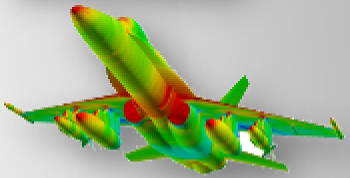


Emphasis on physics-based, predictive modeling

Transition, turbulence, separation, chemically-reacting flows, radiation, heat transfer, and constitutive models, among others.

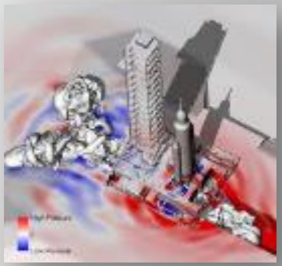
Management of errors and uncertainties

From physical modeling, mesh and discretization inadequacies, natural variability (aleatory), lack of knowledge in the parameters of a particular fluid flow problem (epistemic), etc.



A much higher degree of automation in all steps of the analysis process

Geometry creation, meshing, large databases of simulation results, extraction and understanding of the vast amounts of information generated with minimal user intervention.

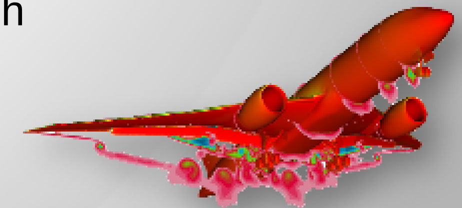


Ability to effectively utilize massively parallel, heterogeneous, and fault-tolerant HPC architectures that will be available in the 2030 time frame

Multiple memory hierarchies, latencies, bandwidths, etc.

Flexible use of HPC systems

Capability- and capacity-computing tasks in both industrial and research environments.



Seamless integration with multi-disciplinary analyses

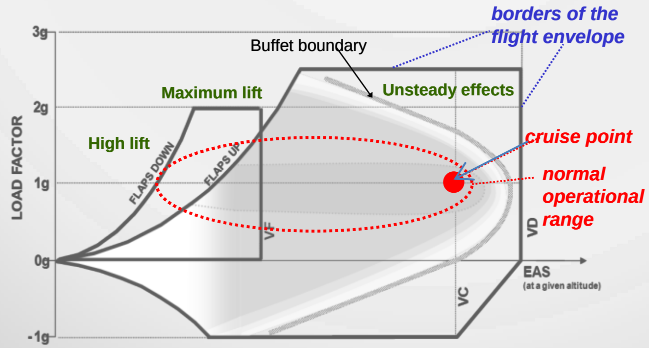
High fidelity CFD tools, interfaces, coupling approaches, etc.

Findings

1. Investment in technology development for simulation-based analysis and design has declined significantly in the last decade and must be reinvigorated if substantial advances in simulation capability are to be achieved.

2. High Performance Computing (HPC) hardware is progressing rapidly
   - Many CFD codes and processes do not scale well on petaflops systems
   - CFD codes achieve only 3-5% of peak theoretical machine performance
   - NASA poorly prepared for exaflops (10^{18} flops) revolution

3. The accuracy of CFD in the aerospace design process is severely limited by the inability to reliably predict turbulent flows with significant regions of separation



CFD accurate only near cruise point

Findings CONTINUED

4. Mesh generation and adaptivity continue to be significant bottlenecks in the CFD workflow, and very little government investment has been targeted in these areas.
   – Goal: **Make grid generation invisible to the CFD analysis process →** Robust and optimal **mesh adaptation methods** need to become the norm
5. Algorithmic improvements will be required to enable future advances in simulation capability.
   – Robust solution convergence for complex geometries/flows is lacking
   – Improved scalability on current and emerging HPC hardware needed
   – Develop "optimal" solvers, improve discretizations (e.g., high-order)
6. Managing the vast amounts of large-scale simulations data will become increasingly complex due to changing HPC hardware.
7. In order to enable multidisciplinary simulations, for both analysis and design optimization purposes, several advances are required: CFD solver robustness/automation, standards for coupling, computing and propagating sensitivities and uncertainties.

Recommendations

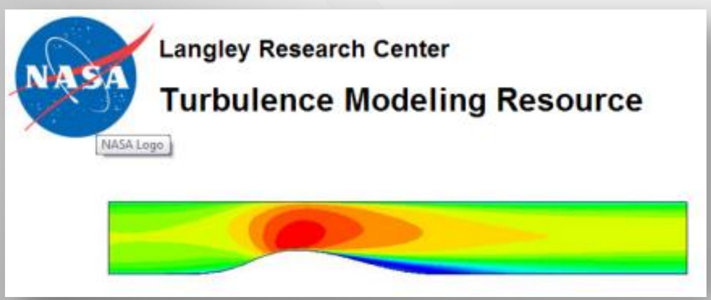
1. **NASA should develop, fund and sustain a technology development program for simulation-based analysis and design.**
   - Success will require **collaboration** with experts in computer science, mathematics, and other aerospace disciplines

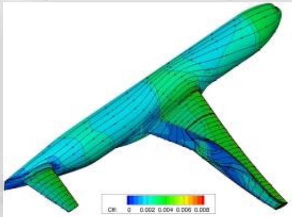
2. **NASA should develop and maintain an integrated simulation and software development infrastructure to enable rapid CFD technology maturation.**
   - **Maintain a world-class in-house simulation capability**
     – Critical for understanding principal technical issues, driving development of new techniques, and demonstrating capabilities

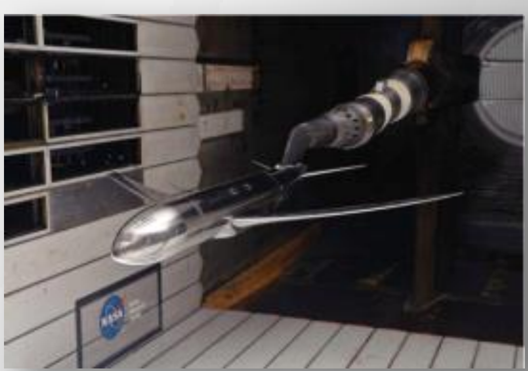
3. **HPC systems should be made available and utilized for large-scale CFD development and testing.**
   - **Acquire HPC system access for both throughput (capacity) to support programs and development (capability)**
     – *improved software development, implementation, and testing is needed*
   - **Leverage national HPC resources**

Recommendations CONTINUED

4. **NASA should lead efforts to develop and execute integrated experimental testing and computational validation campaigns.**
   - High quality experimental test data for both **fundamental, building-block** *and* **complex, realistic configurations**, coupled with careful computational assessment and validation, is needed to advance CFD towards the Vision 2030 goals
     - Experiments to provide data for development of advanced turbulence models/prediction capability
   - **NASA is uniquely positioned** to provide key efforts in this area due to the availability of world-class experimental test facilities and experience, as well as key expertise in benchmarking CFD capabilities







Recommendations CONTINUED

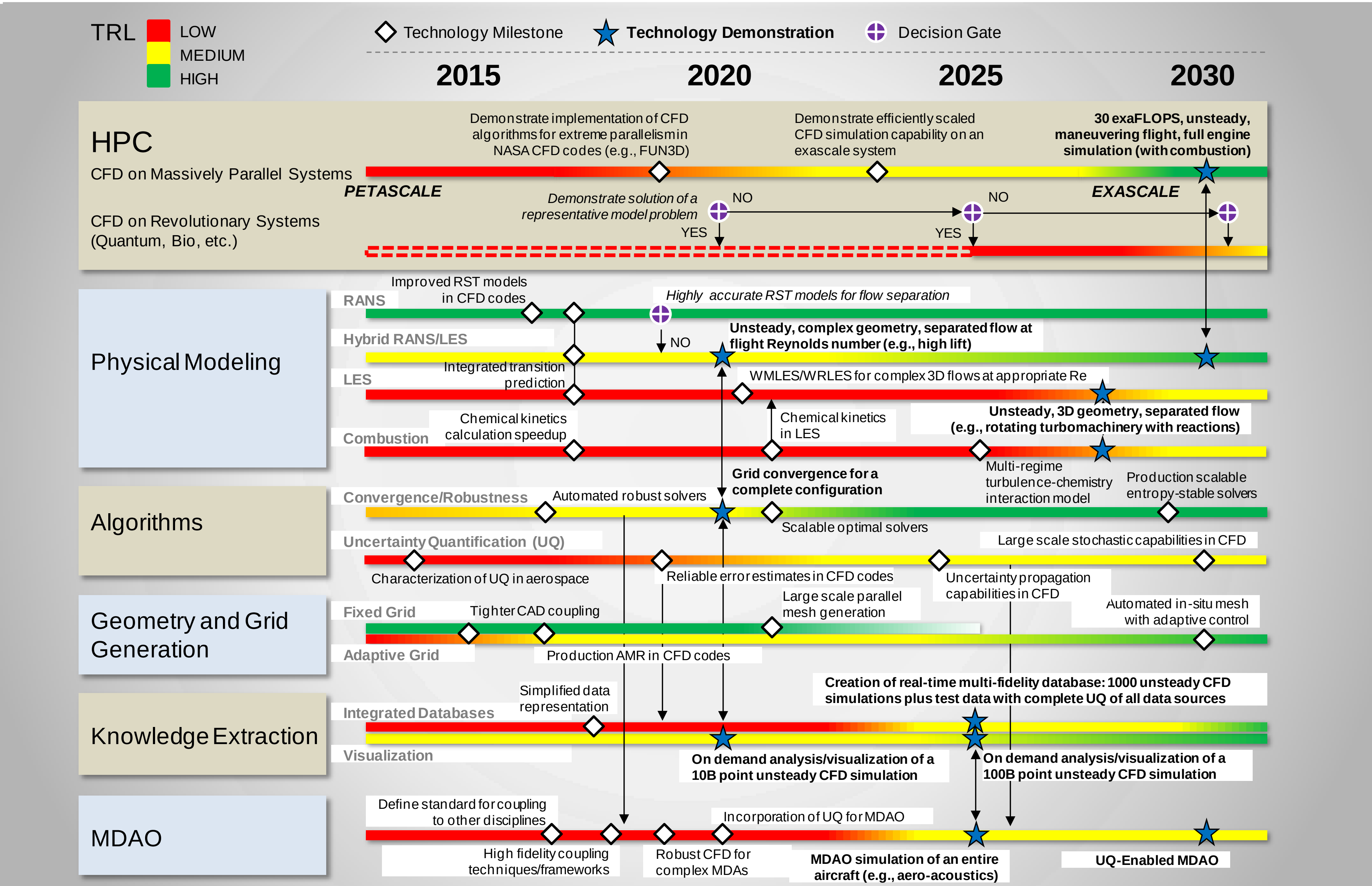
5. **NASA should develop, foster, and leverage improved collaborations with key research partners across disciplines within the broader scientific and engineering communities.**
   - Emphasize funding in **computer science and applied mathematics**
   - Embrace and establish **sponsored research institutes** → provides centralized development of cross-cutting disciplines.

CTR

6. **NASA should attract world-class engineers and scientists.**
   - **Success in achieving the Vision 2030 CFD capabilities is highly dependent on obtaining, training, and nurturing a highly educated and effective workforce**
     - Expand **fellowship programs** in key computational areas
     - Encourage and fund long-term **visiting research programs**

Notional Technology Roadmap

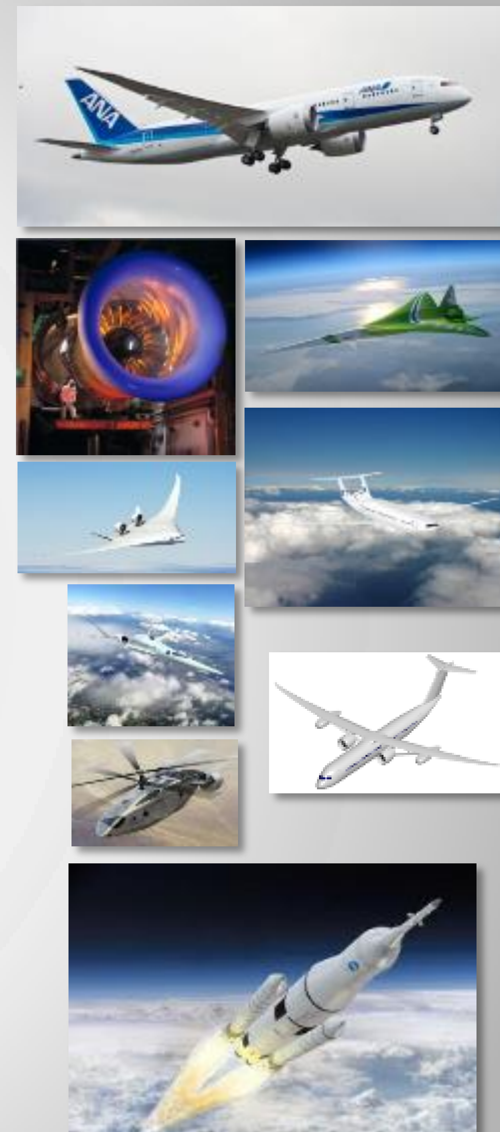
(as suggested by study)



Grand Challenge Problems

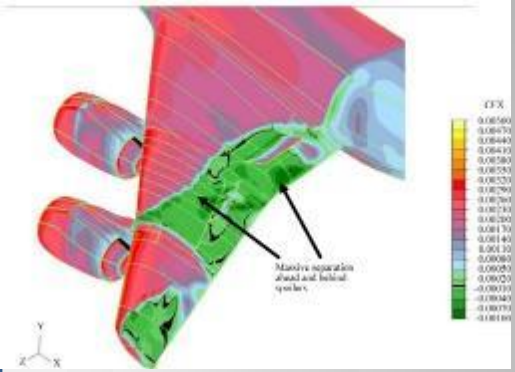
- Represent critical step changes in engineering design capability
- May not be routinely achievable by 2030
- Representative of key elements of major NASA missions

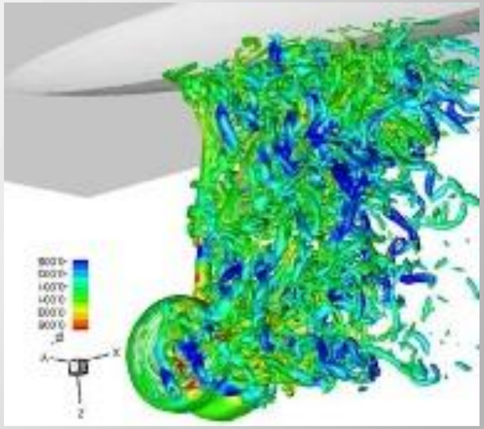
1. Large Eddy Simulation (LES) of a powered aircraft configuration across the full flight envelope
2. Off-design turbofan engine transient simulation
3. Multi-Disciplinary Analysis and Optimization (MDAO) of a highly-flexible advanced aircraft configuration
4. Probabilistic analysis of a powered space access configuration



LES of a Powered Aircraft Configuration Across the Full Flight Envelope

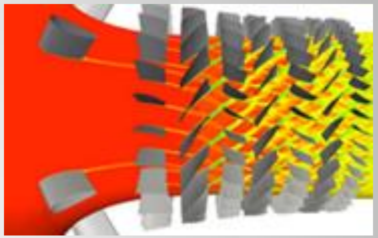
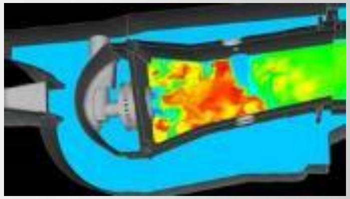
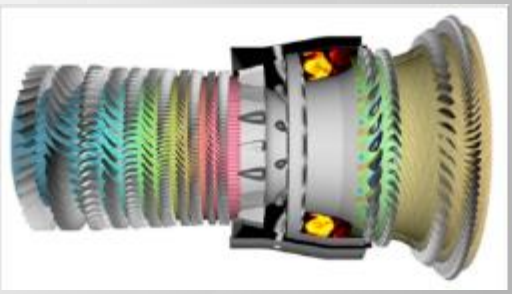
- **Assess the ability to use CFD over the entire flight envelope, including dynamic maneuvers**
- **Assess the ability of CFD to accurately predict separated turbulent flows**
  - Monitor increasing LES region for hybrid RANS-LES simulations
  - Evaluate success of wall-modeled LES (WMLES)
  - Determine future feasibility of wall-resolved LES (WRLES)
- **Assess the ability to model or simulate transition effects**
- **Enable future reductions in wind tunnel testing**





Off-Design Turbofan Engine Transient Simulation

- Measure progress towards virtual engine testing and off-design characterization
- Assess the ability to accurately predict:
  - Separated flows
  - Secondary flows
  - Conjugate heat transfer
  - Rotating components, periodic behavior
- Potential to demonstrate industrial use of WRLES for lower Re regions
- Assess progress in combustion modeling and prediction abilities

MDAO of a Highly-Flexible Advanced Aircraft Configuration

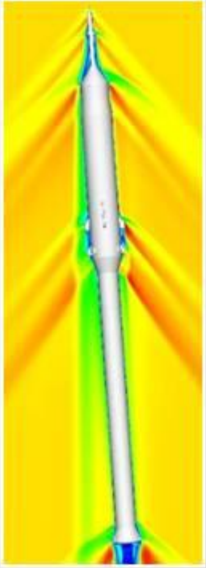
- **Ultimate utility of CFD for aerospace engineering is as component for MDAO**
- **Future vehicle configurations to be highly flexible**
- **Assess progress in analyzing the important multidisciplinary problems: Science of coupling**
  - Time dependent
  - Aero-structural
  - Aero-servo-elastic
  - Aerothermoelastic
- **Assess multidisciplinary optimization capabilities**
  - Availability of sensitivities
  - Performance of optimizations
  - Optimization under uncertainties

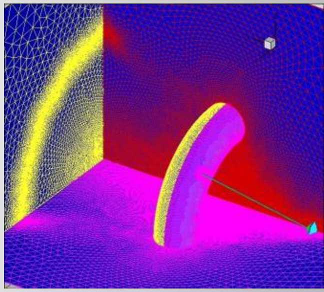


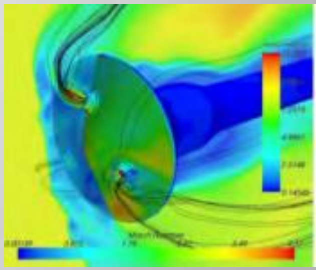



Probabilistic Analysis of a Space Access Vehicle

- **Opening up new frontiers in space vehicle design hinges on development of more capable high-fidelity simulations**
- **Assess specific relevant capabilities**
  - Separated turbulent flows
  - High-speed/hypersonic flows
  - Aero-plume interactions
  - Aerothermal predictions
- **Emphasis on reducing risk through uncertainty quantification techniques**
  - Unique configurations
  - Limited experience base
  - Difficult conditions for ground-based testing







Case Study: LES Cost Estimates

- Wall-modeled LES (WMLES) cost estimates
  - Using explicit, 2nd order accurate finite volume/difference
  - Unit aspect ratio wing, Mach 0.2 flow

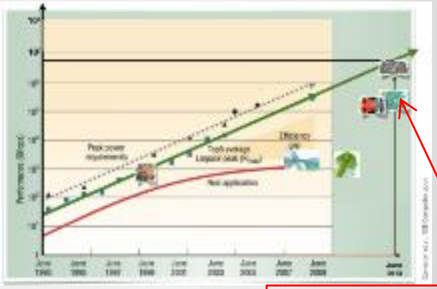
Re_c	N_{dof}	N_{iter}	FLOP	PFLOP/s
1e6	9.0e9	4.6e7	5.2e20	6
1e7	8.5e10	1.5e8	1.6e22	180
1e8	7.5e11	4.6e8	4.3e23	5,000

24 hour turn-around time

- Comparison to current HPC #1 system: Tianhe-2
  - 55 PFLOP/s theoretical peak; 34 PFLOP/s on Linpack benchmark
  - WMLES Re=1e6 feasible today on leadership class machines
- 2030 HPC system estimate
  - 30 ExaFLOP/s theoretical peak
  - WMLES Re=1e8 feasible on 2030 HPC
- Comments:
  - These are capability computations (maxing out leadership HPC)
  - Simple geometry (unit aspect ratio; isolated, clean wing; etc)
  - Algorithmic advances critical for grand challenge problems

CFD Efficiency Enhancement

- **Orders of magnitude reduction in time to solution is a critical need for analysis and design**
  - Unsteady flow computations for complex geometry flows
  - Use of high-fidelity CFD in MDAO
- **Approaches for enhancing CFD efficiency**
  - Effective utilization of existing HPC hardware
    - ❑ Current CFD codes run at 3-5% of machine theoretical peak performance
    - ❑ There is potential for 10x improvement
    - ❑ 2013 Gordon Bell Prize awarded to ETH team that achieved 55% of theoretical peak performance on IBM Blue Gene
  - Exploitation of future HPC hardware
    - ❑ CFD code scalability for exascale architecture
    - ❑ GPUs for desktop engineering work stations
  - Grid adaptation (e.g., adjoint-based)
    - ❑ Promises significant reduction in grid requirement
    - ❑ Automatic viscous grid adaptation remains a challenge
  - High-order methods
    - ❑ Significant potential to speed-up unsteady flow simulations (HO accuracy allows coarser grid, both spatially and temporally)
    - ❑ Need efficient solvers to overcome numerical stiffness



ETH Team Achieved:
55% of theoretical peak

Vision 2030 CFD Findings Summary

- Although CFD has become an integral part of modern aerospace vehicle design and analysis, many technical difficulties in accuracy and modeling *still* persist.

- In the future, to effectively utilize CFD for *all phases* of the design process and in *all corners* of the design space, significant resource investment, coupled with a collaborative, multi-disciplinary research environment, is critically needed.

- A comprehensive study to define a vision of CFD in the year 2030 has been completed →Study recommendations will help guide research investment in CFD development over the next two decades to enable *transformational computational analysis*.

- Once available, the transformational CFD capability will significantly reduce non-recurring product design and development costs, and enable *certification by analysis*.

NASA